DEVELOPMENT OF FUTURE ENERGY MANAGEMENT SYSTEM FOR MICROGRID

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Electrical and Electronic Engineering

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

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Specially dedicated to

my beloved mother, father, sisters and friends

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DEVELOPMENT OF FUTURE ENERGY MANGEMENT SYSTEM FOR MICROGIRD

ABSTRACT

The growth of industries is very essential for the growth of nation. Industries are mainly depending on electrical energy, but unfortunately the sources for electrical energy are depleting and hence the gap between the supplier and the load is continuously increasing. Malaysia has the great potential in implementing solar power generation for household and for industrial usage due to the advantage of solar irradiation from hot sun for all year long. Thus, the electrical network in Malaysia may be penetrated with high capacity of photovoltaic (PV) system in the future. In this project, a microgrid is constructed to monitor and study the behaviour of the network due to PV penetration. Besides that, one of the Demand Side Management (DSM) techniques and Energy Storage System (ESS) results in clipping down the peak in order to flattens the load curve. This help in lowering down the maximum demand during peak hours and reduces the electricity bill of the customers by avoiding the penalty charges from the utility companies. Overall, this energy management system is capable to improve the load factor, saving in the energy bill for the consumers, mitigate the voltage unbalance of the network that is integrated with renewable sources as well as improving the network efficiency which in turn prolongs the life span of three phase machines.

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LIST OF SYMBOLS / ABBREVIATIONS

AC	alternative current
BIPV	building integrated photovoltaic system
CHP	combined head and power
DC	direct current
DG	distributed generation
DSM	demand side management
ESS	energy storage system
HESS	hybrid energy storage system
I/O	input and output
LV	low voltage
NEMA	national electrical manufacturers association
NI	national instrument
PCS	power conversion system
PV	photovoltaic
SI	sunny island 5048
SC	supercapacitor
SEDA	sustainable energy development authority
SOC	state of charge
UPS	uninterruptible power supply
VUF	voltage unbalance factor

CHAPTER 1

INTRODUCTION

1.1 Background

Fossil fuels are the major source of energy in the world today. However, the world is now considering having a more economical and environmentally friendly alternative energy generation system due to the factors of the increasing demand for electric power by both developed and developing countries and also the concern in greenhouse gas emission (Alaa Mohd, 2008). As a result of that, green technologies and renewable energy sources such as photovoltaic solar systems (PV), wind turbines, hydropower turbines, biomass power plant, combined heat and power (CHP) micro-turbines and hybrid power systems had become the main focus of the whole world in solving the energy crisis and environmental issues such as global warming and climate change.

In Malaysia, the total installed generation capacity is 9,041MW. This includes 7,130MW from thermal plants and 1,911MW from hydro plants. According to the annual report of 2012 prepared by TNB, the peak demand for electricity in Penisular Malaysia has increased 2.3% which is from 15,476MW recorded in May 2011 to 15,826MW recorded in June 2012. However, power demand by consumers is never consistent and has a bell-shaped characteristics due to customers' activities that varying from time to time. Consequently, to ensure all varying power demands are met at all times, standby power plants such as gas power plants will be operated by the utility companies to support the grid during peak demand hours, typically from 11 a.m. to 3 p.m. The gas power plants operate by using liquefied natural gas (LNG) that is more costly than coal and diesel. As a result, the cost of generation for a gas power plant is higher than other conventional power plants and thus the cost of electricity (RM/KWH) becomes high followed by the electricity tariff. Therefore, the government had to find an alternative solution to reduce the use of natural gas and other fossil fuels.

Malaysia government had put in a great effort to explore and increase the utilisation of renewable energy sources over the past few years in order to reduce the dependence of fossil fuels and the emission of greenhouse gasses. In December 2011, Malaysia government had implemented a feed-in-tariff to allow electricity produced from renewable sources to be sold to utilities at a fixed-premium price. The feed-in-tariff would be levied at 1% of consumer's electricity tariff and be administered by the Sustainable Energy Development Authority (SEDA), under the Ministry of Energy, Green Technology and Water (Overview of Policy Instrument for Promotion of Renewable Energy and Energy Efficiency in Malaysia, 2005). Hence, this encouraged more people to install and use renewable energy as they can gain back investment in a shorter time by selling back the electricity 4 to 5 times higher than the normal price back to the utilities.

Malaysia is located entirely at the equatorial region with an average daily solar radiation of 4,500 kWh/m^2, and with a sunshine duration about 12 hours (K.H. Chua, 2012). For this reason, solar energy will likely be the key focus due to the suitable geographical location of Malaysia and the available of mature technology in this country; thus, the installation rate of solar panel throughout Malaysia will absolutely increase over the next five years. As photovoltaic system becomes the dominant type of renewable energy in Malaysia, the growth of the Building Integrated Photovoltaic (BIPV) systems also increase which in turn leads to a sustainable and widespread application of PV in the low voltage (LV) distribution network (Malaysia Building Integrated Photovoltaic Project, 2010).

However, the design of the existing LV distribution network does not take into account of the expected technical issues caused by the growth of BIPV systems. A high level of PV panel penetration into the network will caused technical issues such as voltage unbalance, voltage rise, degradation of network efficiency and thermal losses (K.H. Chua, 2012). In the three-phase distribution networks, the load demands is designed in such as way that the distribution of loads are equally over each phase in order to minimize the occurrence of voltage unbalance in the network. Nevertheless, most of the PV systems are to be in single-phase and connected to the LV distribution network through "fit and inform" policy by customers. Consequently, the three-phase voltage of the LV distribution networks will become unbalance can caused the increase of power losses in the network and reduction in the efficiency of distribution network (K.H. Chua, 2012).

Demand Side Management (DSM) is another possible means of reducing peak electricity demand so that utility companies can delay building further capacity and avoid the operation of standby power plants. Besides from reducing the overall load on electrical network, DSM also provides various beneficial which include mitigating electrical system emergencies, reducing the number of blackouts and increasing system reliability. Some other possible benefits can also include reducing dependency on expensive fuels, reducing energy price, and reducing harmful emission to the environment. Thus, DSM applied to electricity system provides significant economic, reliability and environment benefits.

In this project, an energy management system is introduced. It consists of energy storage system (ESS) integrated with several bi-directional inverters and energy storage devices. The system does not reduce the energy consumption of the customers, but the bell-shaped consumption pattern is changed to flat-top by injecting energy from ESS back to the grid during peak demand period. This flat-top pattern is able to prevent customers from maximum demand charge penalty which in term reducing the electricity bills. Furthermore, this system is able to reduce the use of standby power plants by the utility companies, hence minimising the peak demands and the cost of electricity. Apart from that, the energy management system is able to monitor the operating conditions of the network and improve the quality of network voltage affected by the penetration of renewable energy sources and able to mitigate the voltage unbalance factor less than 1%.

1.2 Aims and Objectives

The purpose of this project is to construct a microgrid and develop an energy management system to provide overall power system monitoring, to create control strategies to maintain system performance and security and to reduce cost of operation, maintenance, and system planning by implementing demand side management (DSM) techniques. Besides, this system provides capabilities like predicting system behaviour, anticipatory operation and handling distributed resources as well as random energy demand. Furthermore, with all interconnected nodes with data integration and analysis, this will ease system control and operation. Therefore, the aims and objectives of this project are:

- To introduce the concept of demand side management for residential, commercial and industrial energy user
- To improve low load factor due to variation of load demand from consumers
- To reduce the use of standby power plant during peak demand period and reduce the cost of electricity
- To supply local load using ESS and minimize greenhouse gas emission
- Prevent customers from peak demand penalty and reduction in electricity bills
- To mitigate the voltage unbalance factor to less than 1% caused by random loading and high penetration of renewable energy sources in the network

1.3 Milestones

Table 1.1: Milestone Part 1

Schedule of Milestone (Part 1)		
Milestone	**Description**	**Duration**
1	Research and Proposal	1 week
2	Literature Review	3 week
3	Experiment Setup	5 week
4	Result Analysis	1 week

Table 1.2: Milestone Part 2

Schedule of Milestone (Part 2)		
Milestone	**Description**	**Duration**
1	Design Improvement	5 week
2	System Testing	2 week
3	Result Analysis	3 week

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Microgrid

Global climate change and the current contaminating generation had become a concern to today's industrialised world. Factors concerning for today issues are increasing in demand of electric power, lacking of resources to build power plants and distribution network, insufficient power generation and greenhouse gas emission during power generation (Alaa Mohd, 2008). With an increasing awareness toward the environmental and health effects of these power station's polluting properties, the world had promoted the use of Renewable Energy Sources such as the wind turbines and the photovoltaic panels to be part of future power generation. However, problems occur where these types of energy sources are irregular and hence the generated power is also irregular. In addition, lightning strikes, sudden change of load or occurrence of line fault may cause voltage dips in the system. Therefore, this generates stability, reliability, and power quality problems in the main electric grid (I. Vechiu, 2010). As a result, the microgrid is being analysed as a feasible solution for these problems.

A microgrid is defined as an aggregation of electrical loads and generation. It is a low voltage or medium voltage distribution network formed by microsources or distributed generation (DG) sources, energy storage system, power converters and controllable loads (I. Vechiu, 2010). A microgrid may take the form of shopping centre, industrial park or college campus. The key feature of a microgrid is that it capable to operate whether connected to the grid or disconnected from the grid.

Microgrid can provide grid reinforcement without the need for more generation expansion and can increase the service reliability. Furthermore, microgrid provide additional benefits such as network support during peak demand period, local power quality enhancement by supporting voltage and reduce voltage dips, voltage regulation and power factor correction (A. H. Kasem Alaboundy, 2012). Hence, this system can be used to overcome the irregular and uncertainty in order to provide good quality of load/generation system from the main electric grid point of view.

2.2 Microgrid Overview Modelling

2.2.1 Microsource

Microsource or known as distributed generation (DG) sources are modular power generating technologies like photovoltaic panels, wind turbines, fuel cells and combined heat and power plants are the possible microsouce which are usually designed connected to grid through power electronic devices to inject power into the electrical grid (P.J. Binduhewa, 2010). Normally, the capacity of microsource installed at microgrid is in the range of few kWs to couple of MWs and the installation is close to loads where this will reduce the flow in transmission and distribution circuits with power losses reduction as a consequence (Anestis G. Anastasiadis, 2010). Microsource can play a major role in shaving the peak demand and improve the load factor of the feeder during peak period if the output is corresponding to microsouce. The benefits from improving the load factor include lowering distribution losses, maintaining feeder load to safe limits and enhancing service reliability (C. C. Huang, 2009). Therefore, energy storage units are usually used in conjunction with the installation of microsouce mainly because the storage unit can arrange firmly the microsource output so that electric power can be used when needed and also to charge the storage with electricity from the grid as well as from the microsource. Over time, the microsource control of a microgrid would move the system to a new steady-state, where the power is neither drawn from nor injected into the energy storage unit (P.J. Binduhewa, 2010).

2.2.2 Power Converters

Power converters are the power electronic devices that are used as the crossing point between the energy storage system and microgrid, to control the power flow of the storage devices (bidirectional) and operate the system optimally. However, factors such as power losses due to switching and economical costs are limiting their use in typical electric network (I. Vechiu, 2010). Therefore, a balance between the technical advantages and economical disadvantages must be done. Hence, there are different topologies and architectures of the energy storage system can be used for the same application.

2.2.3 Energy Storage

Increase in electricity demand, stressed and less secured power system operating condition had become the main concern for both utilities companies and power consumers to look for bulk energy storage system. Introduction of energy storage provide beneficial including spinning reserve, power quality improvement, unbalance load compensation, temporary islanding operation, load levelling and peak shaving (Alaa Mohd, 2008).

Peak shaving application shows in Figure 2.1 is particularly favour for industrial plants because the price of electricity varies during hours will give effect to the plant's electricity bill (Alexandre Oudalov, 2007). For example, the cost electricity is low during off-peak demand and the cost is high during peak demand period. Usually, industrial customers operate machines that required significant amount of power during a day. Extra cost during the peak demand is charged according to the highest power demand which result in a high electricity bill. Therefore, energy storage can be used to store energy during off-peak period and supply the stored energy back to utility grid during peak period. This is a typical solution to reduce the load peak and thus reduced the electricity bill.

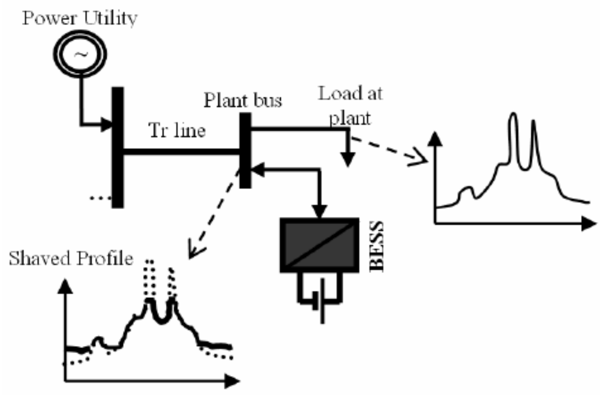

Figure 2.1: Load Peak Shaving by Energy Storage System

In addition to reduce peak demand, energy storage can be used in conjunction with renewable energy resources to increase the reliability and feasibility. This is because the intermittent nature of the renewable sources that is strongly depends on the weather condition will generates stability, reliability, and power quality problems (Ala A. Hussein, 2012). Thus energy storage can be use to support these renewable sources by storing excess generated power, reducing the fluctuation in the generated power and compensating for the forecasting error.

Energy storage system can be classified into two categories namely distributed systems and centralized systems. Distributed energy storage is typically used in medium voltage (≥1MW) system (Gauthier Dupont, 2009). The function is to act as renewable energy storage to provide local load levelling and back-up supply during grid disconnection. Furthermore, this storage system also aims to improve the power quality and enhance the reliability of the network in order to minimize the overall cost of the system operation. In contrary, centralized energy storage system is used in much bigger system (≥20MW) like high voltage grid (Gauthier Dupont, 2009). The purpose of the centralized energy storage system is to support the HV grid by reducing by reducing the peak demand or act as a spinning reserve. Both energy storage system approaches also able to give advantages like transmission stabilization, power factor correction, frequency regulation, voltage control, uninterruptible power supply and carbon emission reduction.

2.3 Energy Storage Architecture

The power system architecture for the renewable energy source and energy storage system can be connected in inline configuration (series connection) where all devices are connected in series along the grid or parallel connection in which the devices are connected to a common bus which can be either DC or AC type.

2.3.1 Series System

Energy storage system in series connection allows a simpler architecture of the system because it required only a few energy storage cells as this system does not need high voltage in the DC bus. Figure 2.2 shows the energy storage bank is connected in series with PV system. In this system, the power generated by PV system is fed to the battery bank resulting in an increase life cycle of the battery (Ala A. Hussein, 2012). As a result, the series configuration reduces the efficiency, power capacity and flexibility of the system because the storage capacity is determined by the size of PV system. Hence, series configuration is not suitable for microgrid and renewable source application.

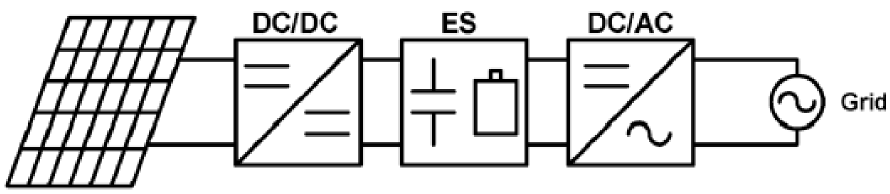

Figure 2.2: Series System

2.3.2 DC Coupled System

DC bus is the common bus used in almost all application. This is because most of the storage devices are DC type and therefore DC common bus ease their implementation. Figure 2.3 shows the configuration of a DC coupled system; an intermediate DC bus couples the PV system and the storage system. The advantage of this topology is that the PV system and storage system work independently without the need of synchronization as in the AC bus (Ala A. Hussein, 2012). Thus the DC bus is more efficient and less costly as compared to the AC bus. However, the deficiency of this topology is that the power flow of the system cannot be controlled since the PV system and energy storage system share the same inverter. As a consequence, this approach suffers from inflexibility and limiting the size of storage system.

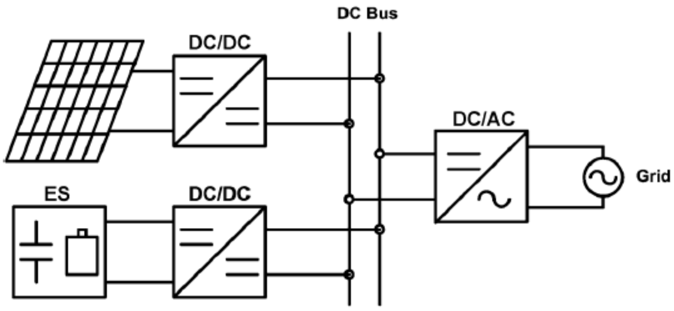

Figure 2.3: DC Coupled System

2.3.3 AC Coupled System

In an AC coupled system as shown in Figure 2.4, the PV system and storage system are both completely independent and do not share common inverter before connected to grid. Therefore, the power flow can be control actively which gives the system flexibility to size and modularize the energy storage. Other than that, AC coupling also allows combination of multiple renewable sources that able to operate efficiently in the system as the generation source and storage has independent path to the grid (Ala A. Hussein, 2012).

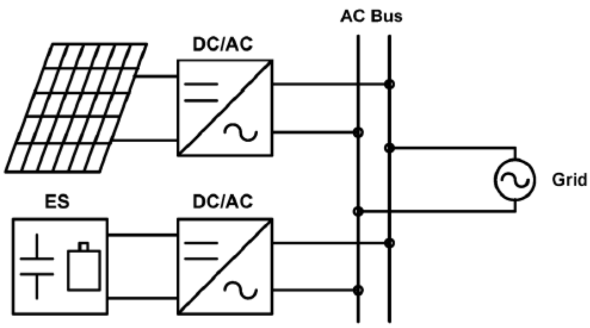

Figure 2.4:AC Coupled System

2.3.4 Storage Type Selection

Battery technologies are evolving fast and are widely charge in terms of their characteristic such as energy and power densities, cost, life-cycle, availability and operating conditions. Hence, energy storage systems have been used in various applications, from portable electronic devices to utility systems. The lead-acid batteries can be categorized into two types called the flooded lead-acid (FLA) battery and valve regulated lead-acid (VRLA) battery. FLA batteries have the characteristic of high life-cycle, low energy density (~25 Wh/kg) and less costly while VRLA batteries have a low life-cycle as well as low energy density (Ala A. Hussein, 2012). Lead acid battery is the most common used battery as it can be frequently charged or discharged. However, this batter suffers from short life span if it is discharge deeply. Therefore, the limitation of lead acid battery is heavy in weight due to lead, toxicity, low energy density, short life-cycle and required periodic maintenance. Nevertheless, due to low costs, lead acid batteries have been used in power system application for number of years.

In distinction, lithium-ion (Li-ion) batteries have a high energy density in range of 90-190 Wh/kg and a comparatively high life-cycle; yet they are more expensive and required an advance circuitry to protect the cells during charging process (Ala A. Hussein, 2012). As a compromise for low cost and high energy density, nickel-metal hydride (NiMH) batteries are able to provide higher energy density and life-cycle compared with VRLA batteries and lower cost compared with

Li-ion batteries. Nickel-cadmium (NiCd) batteries have good characteristic in term of cost-to-cycle ratio, high energy density and tolerance for deep discharge which is suitable for medium-term energy management system (Faruk A. Bhuiyan, 2012). However, its main drawbacks are that cadmium is not environmental friendly due to its toxicity and the batteries suffer from discharging problem at higher temperature.

Sodium sulphur (NaS) batteries are new technologies that have good attribute in terms of high power and energy densities, good efficiency, cost and long life-cycle. The construction of the battery requires special arrangement to prevent heat loss as it needs high temperatures to operate. The battery has been generally used for power quality and renewable energy applications (Faruk A. Bhuiyan, 2012). Another technology, the supercapacitors or ultracapacitors which is still under research and development have the advantages of much higher life-cycle compared with batteries; yet the prices is expensive and is not commercially available (Ala A. Hussein, 2012).

The selection of the type of storage can be crucial. In order to mitigate the low frequency oscillations and overcome the intermittent nature of renewable sources, energy storage with high energy density is required. Meanwhile, high power density energy storage is required to provide high frequency component of power and to deliver and to absorb the transient power. Figure 2.5 shows the energy and power density profiles of different type of energy storage (Haihua Zhou, 2011). Therefore, an energy storage which made up of only battery cells need to be oversized to mitigate peak load demand while energy storage constructed with ultracapacitor has to be oversized to storage large amount of energy to overcome the intermittent of renewable sources and loads. Hence, hybrid energy storage system that provides high power and energy density is needed to operate the energy storage system efficiently.

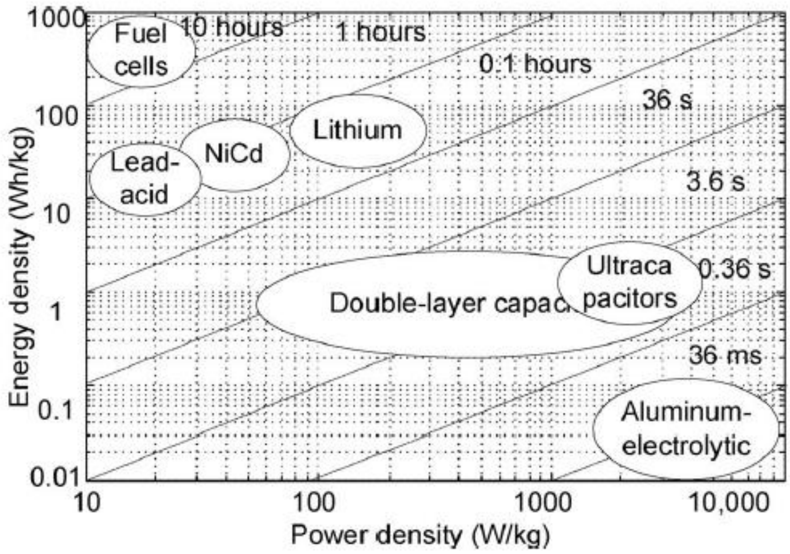

Figure 2.5: Power Density and Energy Density of Different Storages

However, for microgrid application, where power levels are in the range of a few megawatts, the combination battery and ultracapacitor can form very compromising hybrid storage as high energy density and high power density are provided by respectively type of storage (Haihua Zhou, 2011). Hybrid energy storage is able to perform better than batter-alone energy storage. Such system increases the power and battery life span and has the virtues of both high energy density and high power density.

2.4 Functions and Technical Role of ESS in Power System

Energy storage systems have great technical role and variety of functions in power system. The power system application can be categorized in to two major areas known as power quality and energy management. Power quality applications include frequency regulation, transient stability, voltage support, flicker compensation, spinning reserve, unbalance load compensation, whereas load levelling, peak shaving, uninterruptible power supply can be termed as energy management (Faruk A. Bhuiyan, 2012).

In a slow dynamic response system, transient stability occurs due to rapid change of event such as variation of load demand. This situation can be improved by injection or absorption of real power through the energy storage. Besides, when large number of renewable sources connected to the grid or any sudden change in large load generation, this causes the deviation of system frequency (Faruk A. Bhuiyan, 2012). Thus, energy storage can be used as grid frequency support by supplying real power to electrical distribution grid to mitigate the grid frequency deviation.

Voltage sag or voltage dip is a sudden change of voltage magnitude within a short duration in power system which causes power losses and not negligible. In this case, generators can be use to provide real and reactive power to load in order to main voltage within the acceptable range. However, if there is large demand in real and reactive power, energy storage can be use in corresponding with generator to share and provide power to the electrical distribution network to prevent voltage sag (Faruk A. Bhuiyan, 2012). Spinning reserve is defined as the amount of generation capacity that can be used to produce active power over a period of time which has not yet been committed to the production of energy during this period. Similarly, energy storage system can be used as spinning reserve with faster operating speed.

Moreover, an energy storage system can function as an uninterruptible power supply to supply load during power outage. The duration of power supply depends on the state of charge of the battery cells. Furthermore, unbalance load can be compensated by the combination of four-wire inverter and energy storage where the energy storage is controlled to inject or absorb power from each phase to supply unbalance load. For peak shaving and load levelling application, the energy storage system is used to charge during off peak period and discharge during peak period (Faruk A. Bhuiyan, 2012). This application is able to reduce the power consumption during peak demand period and minimize the cost of electricity.

2.5 Introduction to Demand Side Management (DSM)

Power industries in many countries are undergoing reconstructing and deregulation. This is to replace previous monolithic regulated public utilities with competitive power markets. However, under the development of reconstructed power system, problems like transmission congestion, storage capacity, reduction in system reliability and unstable electricity price are included. Therefore, one of the technologies among the various advancements in the power sector known as demand side management (DSM) is introduced.

The very first demand side management approach was introduced in United States (US) in 1970s for the purpose of planning, monitoring, implementation for the activities of electric utilities to influence the usage of electricity by the customers that will result in desired load shape changes by the distribution system such as changes in magnitude and time pattern of the network load demand (Tianyu Luo, 2010). The implementation of DSM mechanisms is often associated with power savings devices, utilities tariffs and incentives and government energy polices in the direction of peak demand mitigation rather than reinforcing the network or set up several power plants to increase the electricity generating capacity. As such, DSM is a fundamental technique with objective that includes elimination of load shape variation, load management, energy efficiency and electrification in order to reduce the planning and operational cost of the network and whole system. Consequently, the benefits derived from DSM are better quality of power supply, reduction in unscheduled interruptions, smoothen the load shape, reduction in production cost and usage of costly fuels, reduction in capital investment, energy efficiency of the equipment is improved and reduction in electricity bills (P. Ravibabu, 2008). All of these benefits can be either short term or long term.

Load shape variation is the indication of the daily or seasonal electricity demand by industrial and residential consumers between peak period and off peak period. It can be classified into six board categories namely peak clipping, valley filling, load shifting, strategic conservation, strategic load growth and flexible load shape as shown in Figure 2.6 (Tianyu Luo, 2010). These techniques are used in appropriate combinations to achieve load management and with the objective of making the load curve as flat as possible. Hence, the implementation of DSM programs is generally to encourage energy user to alter their demand profile by scheduling demand activities at a time that will reduce their energy costs; this in turn helps the utilities by moving the demand away from the peak period.

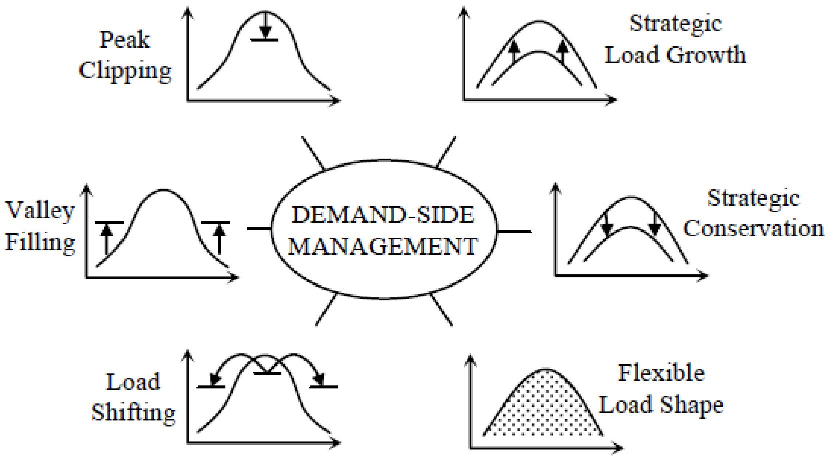

Figure 2.6: DSM Load Shape Categories

2.5.1 General DSM Categories

Generally, there are six main DSM categories as shown in Figure 2.7 help to optimize the current generating base load without the need of reserve capacity to meet the periods of high demand and with the intention to improve the customer productivity and environmental compliance.

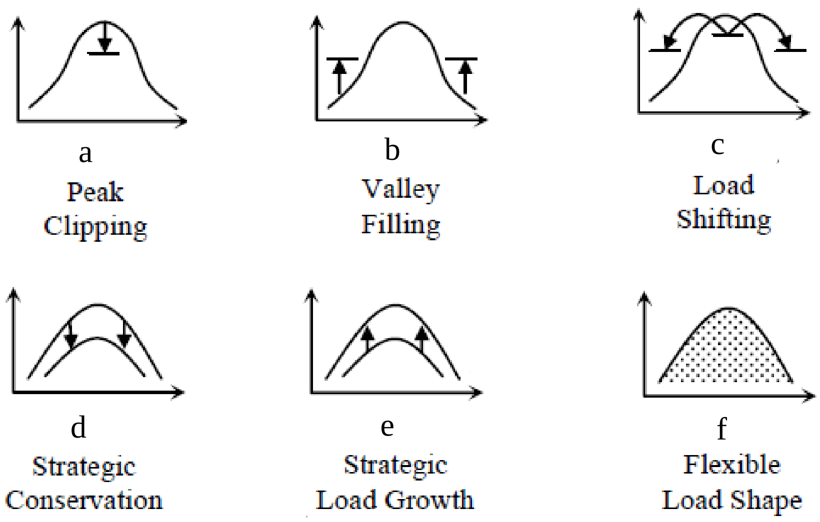

Figure 2.7: DSM Load Shape Categories (a) Peak Clipping, (b) Valley Filling, (c) Load Shifting, (d) Strategic Conservation, (e) Stragetic Growth, (f) Flexbile Load Shape

Peak clipping as shown in Figure 2.7(a) is where the high demand periods clipped by direct load control, while valley filling shown in Figure 2.7(b) focuses on building the off peak demand by applying direct load control (Tianyu Luo, 2010). These two approaches focus on reducing the peak demand and valley load level respectively in order to mitigate the burden of peak demand and increase the security of the distribution network. Load management by peak clipping has least overall effect on the base demand but focus on reducing the peak demand while valley filling increase the base demand by thermal energy storage that displaces fossil fuel loads with peak demand fixed. Load shifting shown in Figure 2.7(c) combines both the load management concept from peak clipping and valley filling where the loads shift from peak period to off peak period (Tianyu Luo, 2010). This approach is widely applied on applications that based on the concept of shifting electricity usage period such as storage water heating, storage space heating, coolness storage, and customer load shifting. The difference in shifting topologies and clipping topologies is that the load is present in overall demand in shifting whereas in clipping it is removed.

Strategic conservation as shown in Figure 2.7(d) indicates the optimization of load shape directed at customer premises through applying the demand reduction methods. However, the modification of load shape involves a reduction in energy sales and it is not worth that utilities would have enough incentive to engage in this activity (Tianyu Luo, 2010). Therefore, in employing energy conservation, the utility planner must consider the long term implication of demand reduction on network planning and operations. Strategic load growth shown in Figure 2.7(e) is the load shape change that refers to large demand introduction beyond the valley filling strategy in future distribution network. Load growth may involve in the increasing of market share of loads that is served by energy conversion and storage system. In the future, load growth may include electrification where it is an electric technology that will increase the energy intensity during the operation by using electricity and also as a motivation on reducing the usage of fossil fuels and other raw materials (Tianyu Luo, 2010). So, it is expected that strategic load growth in the areas of electrification of transport like electric vehicles, industrial processes heating and automation can be considered as strategic load growth. Flexible load shape shown in Figure 2.7(f) concerns with reliability problems in distribution network where the utilities identify the flexible loads of the customers which are willing to be controlled in critical periods in exchange for various incentives (Tianyu Luo, 2010). The implementation of this strategy is suitable for variations of interruptible load, integrated energy management system and individual customer load control device.

2.5.2 Challenges of Implementation DSM

In most developing countries, the awareness of energy efficiency and DSM programs are generally low, and therefore it is necessary to promote the implementation of DSM programs. In the service area of a utility company, beneficial in favour of the sectors and end-users from DSM need to be identified, customized programs developed, cost effectiveness evaluated and a plan to market need to be prepared.

Commonly, due to failure by management to realize the potential benefits of energy efficiency and lack of skilled personnel, most of the industrial and commercial companies are still not able to perform energy audits to collect reliable information on their current operations (Alaa Mohd, 2008). Therefore, in order to for a organization to conduct energy audits or advising on DSM measures, they must consult experts with sufficient knowledge and understanding of DSM system and opportunities. In addition, the experts must be able to demonstrate the competence and comprehensiveness of their assessment consider the accuracy of their assumptions and be aware of the product and safety constraints involved in the plants or companies.

Upon completing an audit, variety of DSM programs are identified to increase the energy efficiency. However, in order to select the suitable load management program, several factors need to be considered such as the total cost to the customer, variations in the prices of electricity and other fuels, avoided penalties resulting from improved electricity system and any potential losses in production when implementing DSM programs (Alaa Mohd, 2008). Hence, a proper financial analysis and project evaluation for the benefits of energy efficiency improvement needs to be carried out when considering setting up of DSM activities.

2.5.3 DSM in Smart Grid

The concept of demand side management in electrical distribution network will be the main vision for future power system development. This will lead to major changes in distribution network design and operation where “smart” concept will be introduced or generally known as smart grid. Smart gird technology is a perception of electrical power distribution network solutions in order to meet the future challenges such as increasing electricity demand, power network infrastructure, distribution generation and the concern of environmental impact during electric generation.

Collection of smart grid solutions include Distribution Automation Asset Management, Demand Side Management, Demand Response, Advance Metering Infrastructure and commercial aggregator control where all these solutions allow utility companies and customer to participate in forming electrical network in the form of scalable smart grid platform (Tianyu Luo, 2010). These solutions have the potential to increase the performance of power system distribution in terms of efficiency and liability while minimize the environmental impact at the same time benefiting utilities and energy users on energy efficiency as well as cost reduction.

Demand side management plays an important role in smart grid application by controlling and influencing energy demand which able to reduce the peak demand and reshape the load profile. This could enhance the sustainability of the grid by reducing the overall cost and carbon emission level. Moreover, this will also lead to the prevention of redundancy infrastructure such as generation capacity, transmission line and distribution network. In general, the essence of DSM in smart grid is to uphold the overall system efficiency, security and sustainability by fully utilize the existing network infrastructure and facilitate low carbon technology into the network. The implementation of DSM functions can also fulfill microgrid objective such as load shifting, load shaving, peak clipping and generation scheduling (Tianyu Luo, 2010). Over this base system, a secondary control of generation and storage devices is developed to cope with the contribution of active power accordingly after load changes.

2.6 Voltage Unbalance Factor (VUF)

In a three phase balance power distribution system, the line-to-neutral voltages are sinusoidal with equal magnitude and phase displaced from each other by 120 degree as shown in Figure 2.8(a). Figure 2.8(b) shows unequal magnitudes or phase angles which will result in unbalance supply or know as Voltage Unbalance Factor (VUF). Therefore, unbalance is one of the disturbances that influence the power quality of power in distribution and transmission grid. The factors that may be caused voltage unbalance in the distribution networks are as follows (K.H. Chua, 2012):

1) Uneven distribution of single phase load across the three phase network
2) Continuous changing of instantaneous demand
3) Unbalance or unstable utility supply

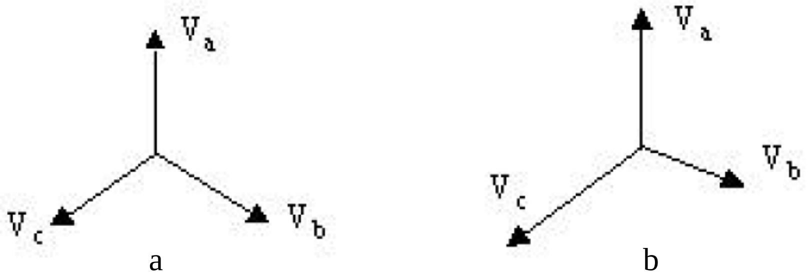

Figure 2.8: Three Phase Voltage Magnitude (a) A Balance System, (b) An Unbalance System

2.6.1 Definition of Voltage Unbalance

The level of voltage unbalance present in a system can be specified using three commonly used definition.

The first definition originates from the theory of Symmetrical Components which mathematically breaks down an unbalance system into three balanced system. These three are called positive sequence, negative sequence and zero sequence system shown in Figure 2.9. In a balanced system, both negative and zero sequence system do not exist. This definition is also commonly known as European standards (Annette von Jouanne, 2001).

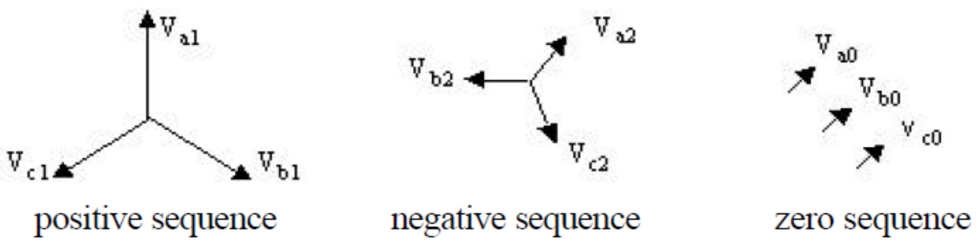

Figure 2.9: Symmetrical Components of an Unbalanced System of Voltages

According to the European standards, Voltage Unbalance Factor is defined as the ratio of negative-sequence (V-) to positive-sequence (V+), as expressed below (P. Trichakis, 2006):

$$VUF(\%) = \frac{V^{+}}{V^{-}} \times 100 \tag{2.1}$$

The negative and positive sequence of the system voltage can be computed by the following expression:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} V^0 \\ V^+ \\ V^- \end{bmatrix} \tag{2.2}$$

where V_a, V_b and V_c are the three phase line voltages and V^0, V^+ and V^- are the positive, negative and zero sequence voltage components respectively.

The second definition is the NEMA (National Electrical Manufacturers Association) standard. In the NEMA standard, the line voltages are used as opposed to the phase voltages. This is because, when phase voltages are used, the phase balance is not reflected in the % unbalance and thus phase voltages are seldom used to calculate voltage unbalance. The definition of NEMA standard is given by the following equation (P. Pillay, 2001):

$$VUF(\%) = \frac{MaximumDeviationfromAverageLineVoltages}{AverageLineVoltages} \times 100 \tag{2.3}$$

Third definition is the IEEE standard. The IEEE uses the same definition of voltage unbalance as NEMA. However, the only difference is that IEEE uses phase voltages rather than line-to-line voltages. Similarly, the phase angle information is lost since only magnitudes are considered (P. Pillay, 2001).

$$VUF(\%) = \frac{MaximumDeviationfromAveragePhaseVoltages}{AveragePhaseVoltages} \times 100 \tag{2.4}$$

The IEEE definition is mathematically rigorous compared to NEMA definition. Hence, when calculating the voltage unbalance the two definitions can cause different results.

Table 2.1 shows the voltage unbalance statutory limit. In Malaysia, the statutory limit of the voltage unbalance is 1% (The Malaysia Grid Code, 2006) which is much stringent as compared to 1.3% in the UK and 2% in EU (P. Trichakis, 2008). Voltage rise or voltage tolerance boundary is also an issue to be concern in the three-phase power distribution system. It is define as the nominal voltage rating for the utilities to regulate the service delivery and operating tolerance. In Malaysia, the tolerance boundary is set at a range of +5% & -10% for primary distribution with voltage level of 240V (Tenaga Nasional Berhad, 2006). By having the tolerance boundary range, the equipment will perform satisfactory in conformance with product standards throughout the voltage range provide from the utilities.

Table 2.1: Voltage Unbalance Factor Statutory Limit

Country	Voltage Unbalance Factor Statutory
Malaysia	1.0%
UK	1.5%
Other EU	2.0%

2.6.2 Effect of Voltage Unbalance

Voltage unbalance is regarded as a power quality problem of significant concern at the electricity distribution level. Unbalance voltage can result in adverse effects on equipments and on the power system. Under unbalance condition, the power system will experience more losses and heating effects and thus the distribution network will become less stable.

The greatest effect of voltage unbalance is on the three-phase induction motors (Annette von Jouanne, 2001). Three phase induction motors are one of the most common loads on the network and are found in large number especially in industrial sectors. The adverse effect of unbalance voltage on induction motors can be describe using the method of symmetrical components where in an unbalance three-phase system, the voltages can break down into three balance system namely positive, negative and zero sequence. However, in the case for machine, the zero sequence components will be zero as motors are typically connected delta or underground wye and hence there is no path to neutral for zero sequence components to flow.

Therefore, the unbalance motor voltage contains positive and negative sequence components which have opposing phase sequence for example “ABC” and “ACB” respectively as shown in Figure 2.10.

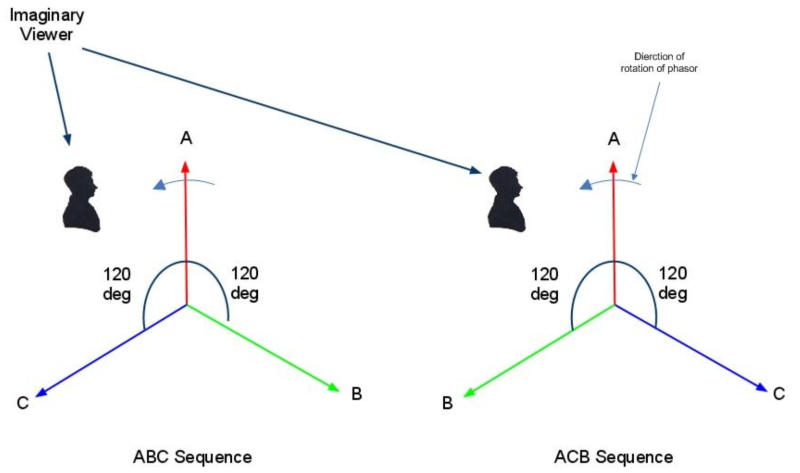

Figure 2.10: ABC and ACB Phase Sequence

The positive sequence voltage produces the desired positive torque, whereas the negative sequence voltage produces an air flux rotating against the rotation of the rotor, thus generating an unwanted negative (reversing) torque (Annette von Jouanne, 2001). Therefore, in this condition, there will be a reduction in the net torque and speed and also increased motor noise. Furthermore, the negative sequence component in the unbalanced voltages generates large negative sequence currents due to the low negative sequence impedance, which increases the machine losses and temperature. According to NEMA, voltage unbalance of 1 percent at the terminal of fully loaded motor can cause the increase in heating by 6 to 10 percent (Motors and Generators, 1993). As a result, the effect of unbalance reduced efficiency and decreased life of the motor.

CHAPTER 3

METHODOLOGY

3.1 Microgrid Overview

Based on the literature review in Chapter 2, a microgrid is formed by microsources, storage system, power converters and loads. Therefore, a microgrid is set up to study, analyse and monitor the behaviour of the power system when photovoltaic systems are integrated to the microgrid. In addition to that, a energy management system is developed to mitigate the problem caused by photovoltaic systems in order to improve the efficiency and power quality of the distribution network. Figure 3.1 shows the electrical diagram of the microgrid.

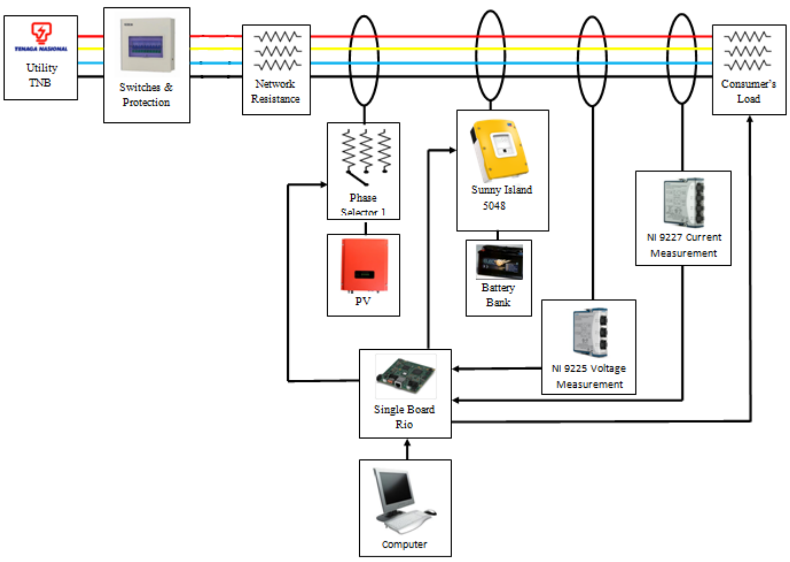

Figure 3.1: Electrical Diagram of Microgrid

In this development, the microgrid is connected to TNB utility to obtain three-phase supply through the protection switches which is used to enhance personnel safety. At the end of the microgrid, a custom made load is connected to the grid to emulate a typical electrical power consumer. In the middle of the grid, photovoltaic system and Sunny Island 5048 are connected which act as a microsource and an energy storage system respectively.

3.2 Microgrid Setup

Figure 3.2: Microgrid Setup

Figure 3.2 shows the experiment setup of the microgrid. In this project, National Instrument (NI) Single-Board Rio 9632XT is used as a platform to simplify development when designing control, monitoring and system testing; therefore, with the advance features of this platform, it is use as the central control system in this project. From the 110 3.3V (TTL/5 V tolerant) DIO lines embedded in the board, the I/O is sufficient enough to trigger the routines of the load bank as well as other controlling routine. Furthermore, the Connector for C Series Module in the board are used with the NI 9225 3-Channel Voltage Measurement and NI 9227 4-Channel

Current Measurement to measure and monitor the voltage level and output current in the microgrid.

The transmission line model is emulated by a series of network resistance acting as the line resistance. Three-phase controllable load bank is constructed with a series of resistor to emulate a typical electrical power consumer. The NI Single-Board Rio 9632XT is used to turn on/off the load bank via the solid state relay. The load in each phase can be varied from 0 watt to 1000 watt in step of 200 watt.

A solar inverter with power rating of 1500 watt is used as microsource in this project. Due to the fact that the sunlight is inconsistent and dependent on the weather, the PV panel is not suitable for the laboratory purpose. Hence, the energy source of PV inverter is provided by a battery bank that replaces the PV panel to supply a continuous DC power. The DC power is converted into AC power via the inverter and supplied to one of the phase through a phase selector. The phase selector can be controlled to connect PV inverter to one of the phases.

The Sunny Island 5048 is a bidirectional inverter. It acts as an energy storage system to absorb and deliver power to the electrical network. Besides that, it also function as an uninterruptible power supply (UPS) which enable the microgrid continue to operate when power outages occur.

3.3 Hardware and Devices Functional Description

3.3.1 Single-Board Rio 9632XT

Figure 3.3 shows the Measurement and Automation system. In this project, Single-Board Rio acts as the central processing unit in testing, controlling as well as monitoring the overall system. With the advance features that in internally built-in on board such as integrated analog and digital I/O, real-time controller, reconfigurable FPGA and also the connector for C series module, all of these features simplify the system design.

Figure 3.3: Measurement and Automation system

3.3.2 Transmission Line Model

The transmission line model in Figure 3.4 is used to emulate the resistance of the line. It consists of four set of resistors value that can be connected to three-phase-four-wire system. The resistance for each phase can be varied from 0.11 ohm to 0.33 ohm.

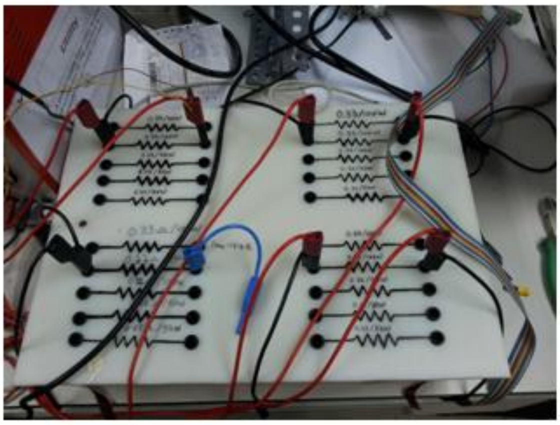

Figure 3.4: Transmission Line Model

3.3.3 Controllable Load Bank

The custom made controllable load bank in Figure 3.5 consists of a series of resistors and solid state relay. Figure 3.6 shows the per-phase circuit of the load bank. The load in each phase can be varied from 0 watt to 1000 watt in step of 200 watt by turning on/off the solid state relay. To easy the understanding of loading condition in the three-phase system, the loading condition will be represented in a matrix form as [A B C], where A, B and C are the load values. For example, [1000 0 0] represents the load at phase A is 1000 watt where load at phase B and phase C are zero.

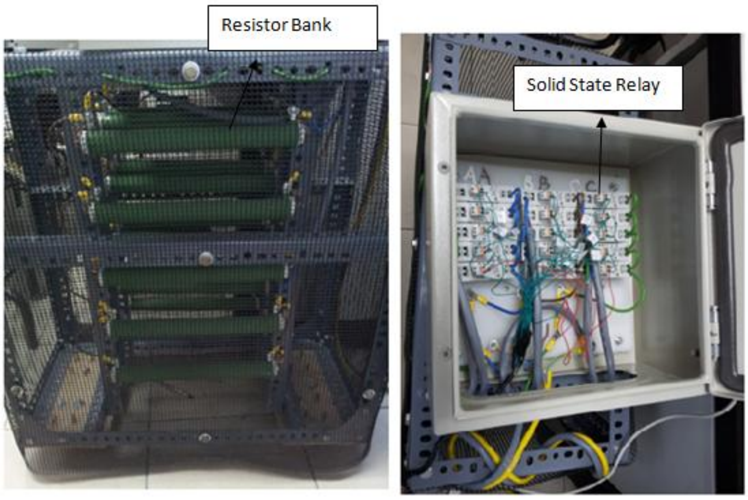

Figure 3.5: Controllable Load Bank

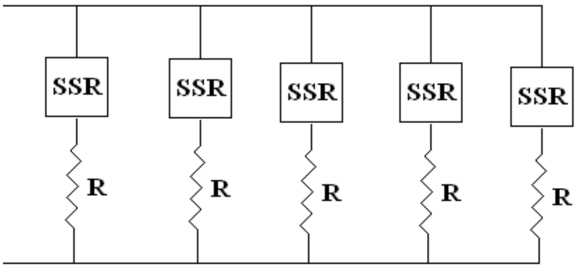

Figure 3.6: Per-phase Circuit Diagram of Load Bank

3.3.4 Photovoltaic System

The photovoltaic (PV) system shown in Figure 3.7 consists of inverter and battery bank. The battery bank emulates a PV panel to provide power up to 1500 watt. The DC power is converted into AC power via the PV inverter and connected to the three-phase distribution network via phase selector. The phase selector is controlled by solid state relay which is connected to the integrated I/O port of the Single-Board Rio.

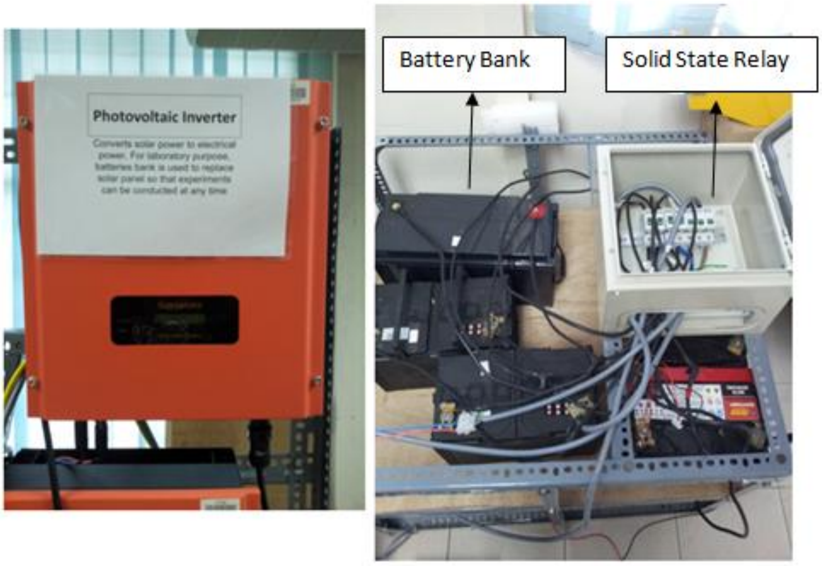

Figure 3.7: Photvoltaic System

3.3.5 Sunny Island 5048

Sunny Island 5048 shows in Figure 3.8 is a bi-directional inverter which forms the basis of a self-sufficient islanded AC microgrid. Therefore, this device is able to provide power supply during power outage to ensure continuous power supply to the network. Furthermore, this power inverter with battery bank is also used as an energy storage system as it can be control to either inject or absorb power according to the network conditions. Cost, rating, energy capacity and lifetime are the criteria’s for choosing the suitable battery for the battery bank. A summary of a review of various technologies is shown in Table 3.1 (K.H. Chua, 2012).

Figure 3.8: Sunny Island 5048

Lead-acid battery is chosen in this project because of its low initial cost. The capacity of each lead-acid battery is 120 Ah which is commercially available. Therefore, the battery bank consist of four batteries connected in series with a total capacity of 480 Ah which able to provide energy storage up to 5760 Wh. Hence, Sunny Island will take over the load that is connected to it when there is lack of power from the utility while it will charge battery bank when there is excess power from the grid to maintain the balance in the network.

Table 3.1: Design Consideration for Energy Storage Device

Energy Storage Technology	Advantages	Disadvantages
Lead-acid batteries	Low initial cost	Short lifetime (3 to 7 years)
NiMH batteries	Reliable, long lifetime	10 times as expensive as lead-acid batteries
Hydrogen fuel cell (PEMFC)	High power density	Expensive, short lifetime
Lithium ion (Li-Ion)	High specific energy power, long lifetime	Expensive

3.4 Software Application

In this project, the software used for the designing the energy management system is LabView by National Instrument. LabView is a graphical programming tool for test, measurement, and automation and is widely used as a virtual instrument tool. It allows developer to develop sophisticated measurement, test and control system using intuitive graphical icon and wires that resemble a flowchart. One of the major advantages of Labview apart from being simple to use is that it has the ability to work with a number of hardware interfaces using real time analog and digital signals. LabView programs work as simulation or data acquisition. By using this software to program the application, LabView provides a real-time view of the entire system on a primary screen and live view of all analog values displayed. Hence, LabView provides the flexibility to display all analog signals in graph and record them.

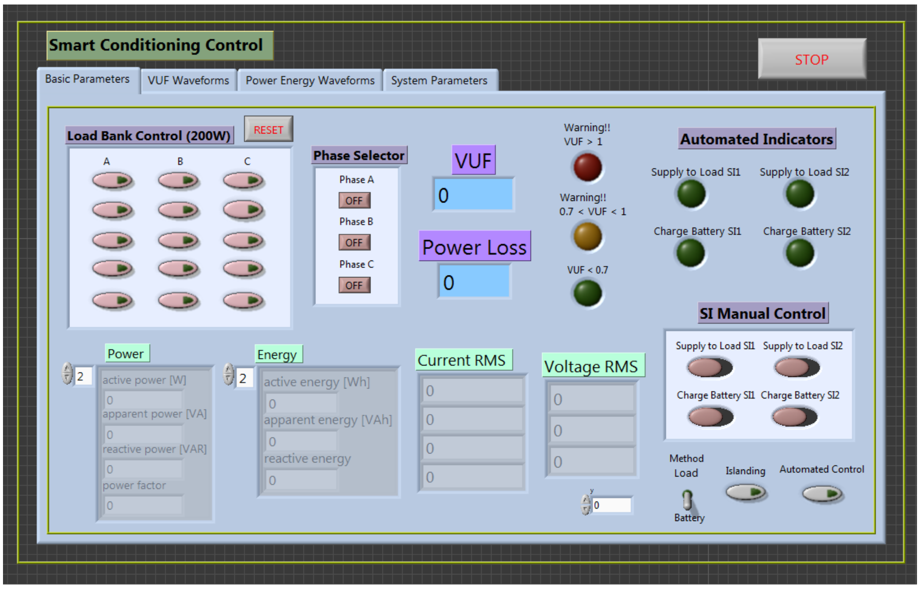

Figure 3.9: Main Control Panel

Figure 3.9 shows control panel of the energy management system developed in LabView. In the basic parameters tab, load control, phase selector control, Sunny Island control and measurement of power, energy, voltage, current and VUF can be found. There are 3 indicators lights to indicate the voltage unbalance factor level. Besides that, there are also two method of operating the system namely manual control or auto control. The manual control allows the user manual control the Sunny

Island to either supply power to load or absorb power to charge batteries via the "SI Manual Control" menu. While in auto control, the energy management system will operate the Sunny Island based on the control algorithm. The "Automated Indicators" shows the connection of Sunny Island for different scenario.

In Figure 3.10 and Figure 3.11, the waveforms for VUF, power and energy is shown. These graphs provide a good view for user in the dynamical change of VUF, power and energy.

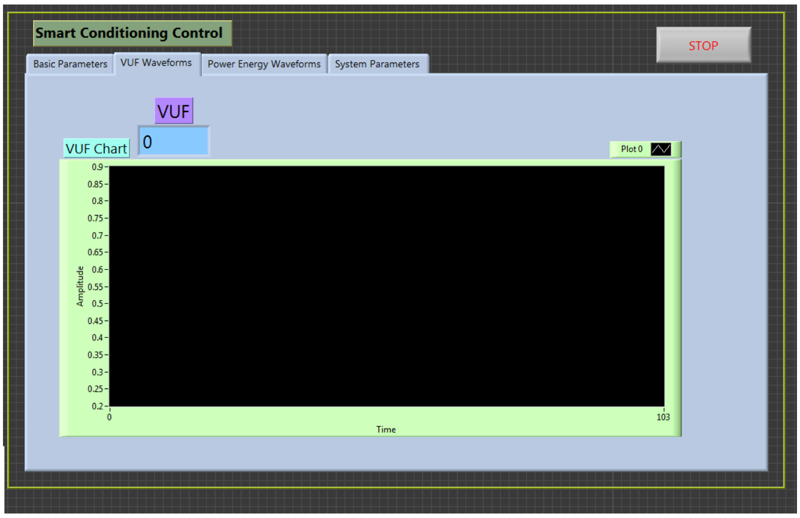

Figure 3.10: VUF Waveform Display

Figure 3.11: Power and Energy Waveform Display

3.5 Design Architecture

3.5.1 Peak Demand Clipping Algorithm

Figure 3.12 shows the control algorithm of the peak demand clipping application. The threshold for the allowable maximum demand is set at 2.5 kW. Therefore, when the power demand of the load exceeds the threshold, the energy management system will inject power from the energy storage system via bi-directional inverter to support the network.

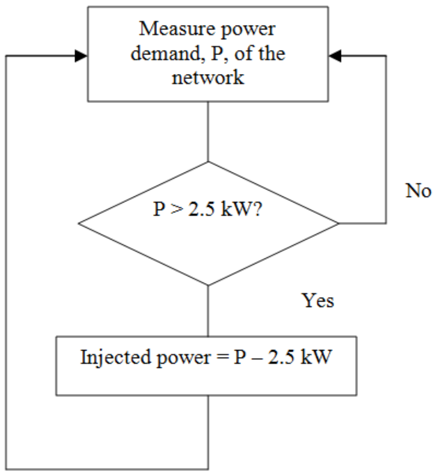

Figure 3.12: Flow Chart of Peak Demand Clipping

3.5.2 Voltage Unbalance Mitigation Algorithm

For VUF mitigation, the threshold of acceptable VUF is set at 1% according to Malaysia Grid Code. Therefore, when VUF exceeds 1%, the energy management system will check whether the unbalance is caused by PV inverter or due to uneven load distribution. If injection of power from PV inverter is the contributing factor, the excess power will be channel to energy storage system to charge the batter cells. If unbalance is caused by uneven load distribution, the energy management system will inject power to the phase with highest load from the energy storage system. Figure 3.13 shows the flow chart for VUF mitigation.

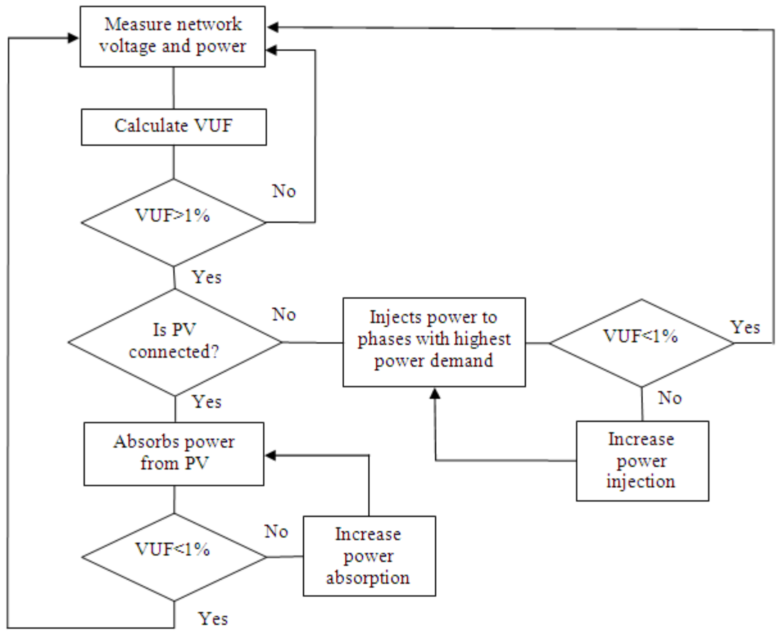

Figure 3.13: Flow Chart of VUF Mitigation

3.5.3 Overall Energy Management System Algorithm

The voltage unbalance factor (VUF) in the network is calculated using the NEMA standard as shown in Equation 2.3 in Chapter 2. Base on the Malaysia electrical grid code, the technical requirement of VUF in the distribution network should be maintain below 1%. Hence, this system is designed to react such a way to limit the VUF from exceeding 1%. The architecture in designing this system is to react when VUF reach 0.8%. When the VUF is greater than 0.8%, the system now will compare the voltage at each phase. For example, if mode 1 is selected and phase A is having the highest lowest voltage, the PV inverter will be channelled to phase A via phase selector or when PV inverter is not connected to the network, Sunny Island will be connected to phase A and supply to load. While mode 2 is selected, the demand of power decreased in phase A, the PV may cause unbalance if the load in phase A demand is less than the power generated by the PV. At this moment, the battery charger will be turned on to store the excess power into battery to maintain the balance of all the three phases. The flow chart of the system is shown in Figure 3.14.

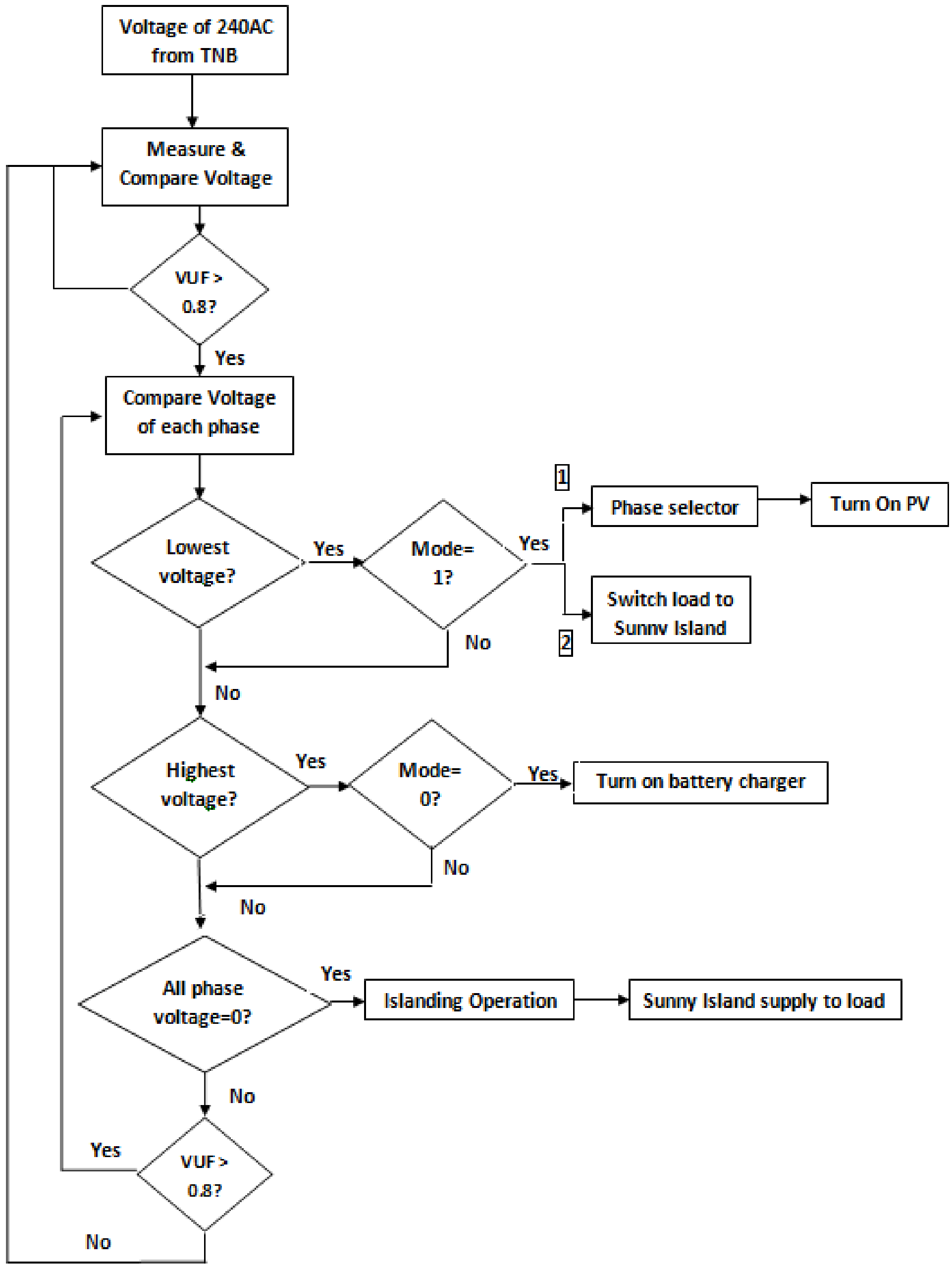

Figure 3.14: Flow Chart of Energy Management System

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Preliminary Experiments

4.1.1 Balance Load Network

In this experiment, the loads were distributed equally across three phases in the distribution network. The loading condition in each phase increases from [0 0 0] up to [1000 1000 1000] in a step of 200 watt. Inherently, the network has VUF in the range of 0.4% to 0.55% as shown in Figure 4.1. So, the increment of balance load in three-phase system does not increase the VUF.

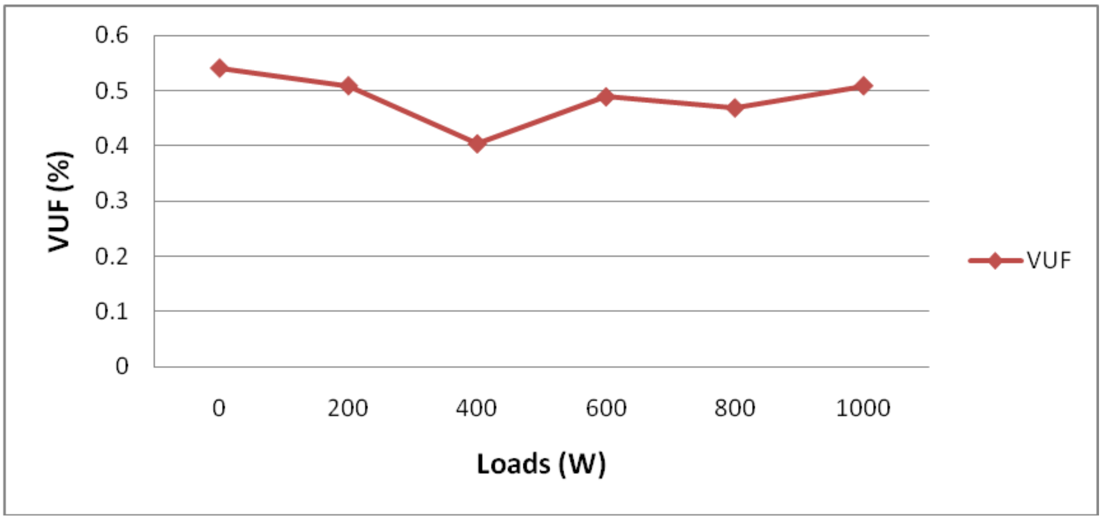

Figure 4.1: VUF for Balance Load Network

4.1.2 Balance Load Network with PV System Connected at Phase A

Figure 4.2 shows the VUF with balance load and PV system connected in at Phase A. Before correction of the energy management system, it was found that the VUF falls beyond the statutory limit of 1%. This is due to injection of PV power into phase A, consequently this caused the increment of voltage in Phase A. However, the VUF decreased gradually when the load regularly increased because the ratio of PV power to the total amount of load becomes less significant. After correction from the energy management system, it was found that the VUF had been suppressed to minimal value of 0.5%. In fact, the energy management system has channelled the excessive power from PV system to charge the energy storage.

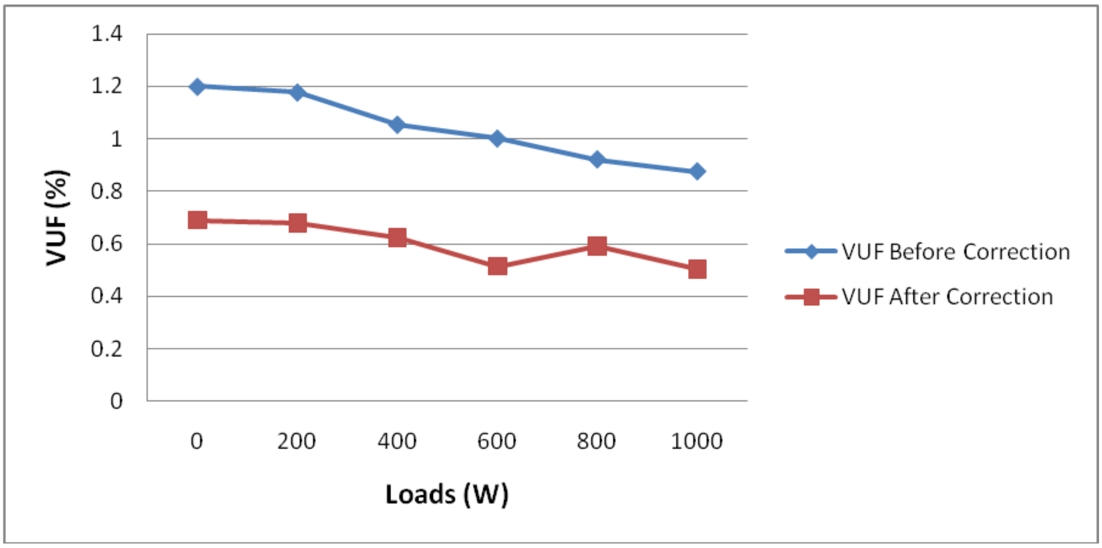

Figure 4.2: VUF for Balance Load Network and PV System Before and After the Correction of the Energy Management System

4.1.3 Unbalance Network with Load and PV System Connected at Phase A

In this case study, the loads and PV system were connected at phase A while phase B and Phase C have no loads to create unbalance load condition. Before correction, it was found that the VUF behave in U-shaped with the increment of load at phase A. This was due to the fact that the PV power had offset the load from 200 watt to 1000 watt; hence the VUF is reducing in this region. As the PV power generated is equal to the load, the VUF reach its minimal value. The further increment of load after 1000 watt will cause the increment of VUF because the PV power had no longer sufficient to compensate the load. After the correction of energy management system, the excess power from PV was charged to the energy storage starting from load of 200 watt to 1000 watt. This has successfully kept the VUF below 1% when the demand is low. However, due to the fact maximum power that can be provided by PV system is 1200 watt, therefore, after 1200 watt the VUF will rise as shown in the red line of Figure 4.3.

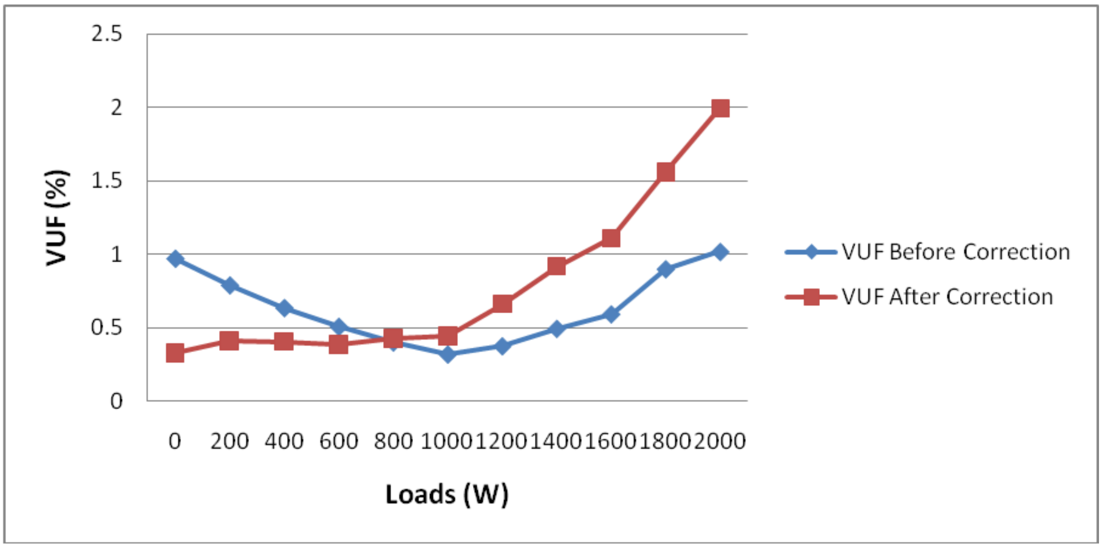

Figure 4.3: VUF for Unbalance Load Network with Load and PV System at Phase A Before and After the Correction of Energy Management System

4.2 Improved setup and Experiments

4.2.1 Peak Demand Clipping

Experiment was carried out to determine the ability of energy management system to limit the maximum peak demand in conjunction with energy storage at a particular level by peak clipping approach. In this case study, the threshold of the maximum power demand for the energy management system was set at 2.5 kW. From the result shown in Figure 4.4, notice that when load further increase from 2.5 kW to 3kW at 36s, the power demand is maintained at 2.5 kW regardless of any variation in the actual demand. This is because as the power demand exceeds the threshold of 2.5 kW, the energy management system begins to inject power from the energy storage to the network. Hence, the peak demand was successfully suppressed.

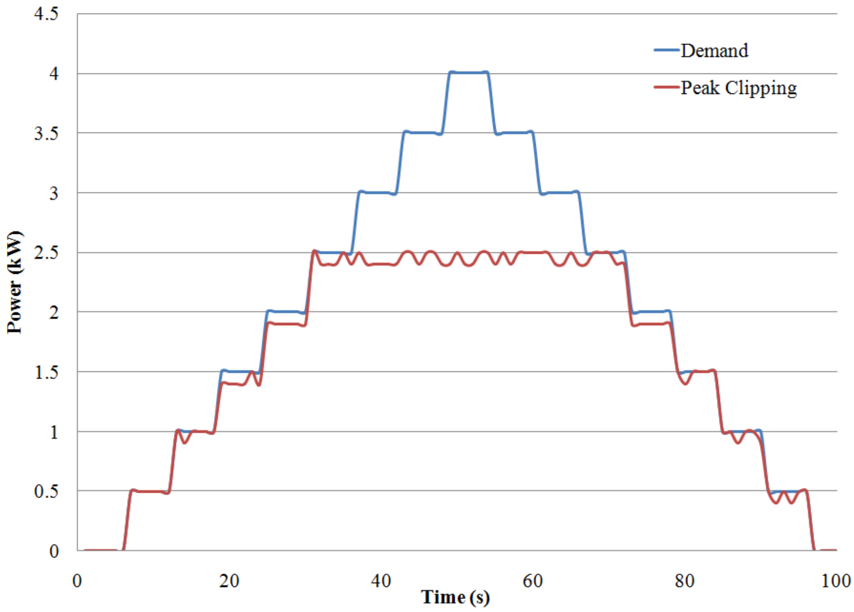

Figure 4.4: Peak Clipping

The operating duration of the energy storage was strongly depends on the current state-of-charge (SOC) of the batteries. Therefore, during the off peak period, the energy management system will charge the energy storage in order to recover the SOC of the batteries. Table 4.1 shows the operating duration of the energy storage for various load demand.

Table 4.1: Voltage Unbalance Factor Statutory Limit

State-of-charge (%)	Capacity (kWh)	Load operating time (hour)				
		1 kW	**2 kW**	**3 kW**	**4 kW**	**5 kW**
10	0.576	0.576	0.288	0.192	0.144	0.1152
20	1.152	1.152	0.576	0.384	0.288	0.2304
30	1.728	1.728	0.864	0.576	0.432	0.3456
40	2.304	2.304	1.152	0.768	0.576	0.4608
50	2.88	2.88	1.44	0.96	0.72	0.576
60	3.456	3.456	1.728	1.152	0.864	0.6912
70	4.032	4.032	2.016	1.344	1.008	0.8064
80	4.608	4.608	2.304	1.536	1.152	0.9216
90	5.184	5.184	2.592	1.728	1.296	1.0368
100	5.76	5.76	2.88	1.92	1.44	1.152

4.2.2 Uneven Power Demand

An experiment was conducted to evaluate the ability of energy management system to mitigate voltage unbalance caused by load variation in the network. In this case, the load is connected to Phase A. Figure 4.5 shows the experiment result of VUF and power demand of load in the network. From the result, observed that the initial VUF of the network from 0.5% drop to 0.35% when the first load was applied. This is because initially the voltage at Phase A is higher than other two phases and consequently dropped after the load applied; hence the three phase voltages tend to become more balance. As the power demand increase, the voltage at phase A continues to drop and caused the VUF increase up to the maximum of 1.2%.

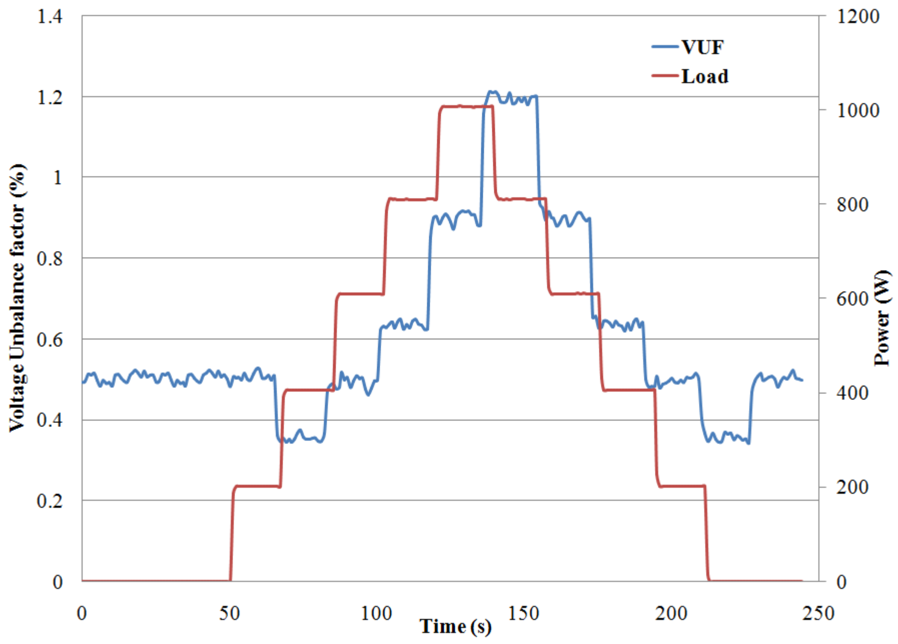

Figure 4.5: Load Demand and VUF for Load Connected at Phase A

In order to mitigate the voltage unbalance caused by uneven power demand, the energy management system supply power from the energy storage to the phase that required higher demand to maintain the voltage level and hence the voltage balance among three phases is achieved. Figure 4.6 shows the VUF of the network after mitigation by the energy management system. As the load continues to increase after 135s, the system detects that VUF exceed the threshold of 1% and power from energy storage was supplied immediately to the network and minimize the VUF down to 1%.

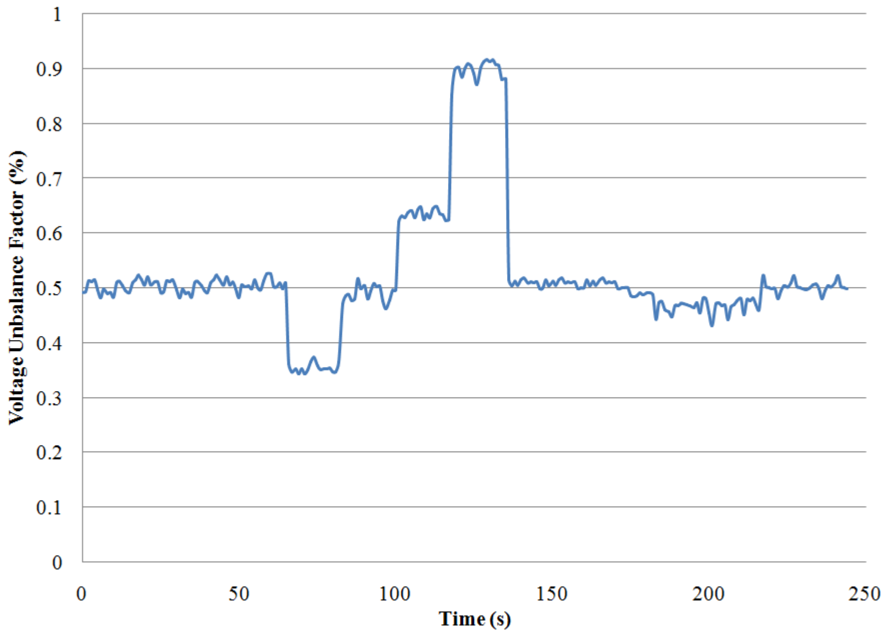

Figure 4.6: VUF for Uneven Demand After Mitigation

4.2.3 Uneven Power Demand with PV Inverter and Load Connected at Different Phases

In this experiment, the PV inverter is connected to Phase A while the load is connected to Phase C. The aim of this experiment is to evaluate the voltage condition of the network when the PV inverter and load are connected at different phases. Figure 4.7 shows the experiment result of the parameters from the network. The highest VUF recorded in this experiment is 2.85%. As a result, the increase in PV power causes deterioration of voltage unbalance of the network.

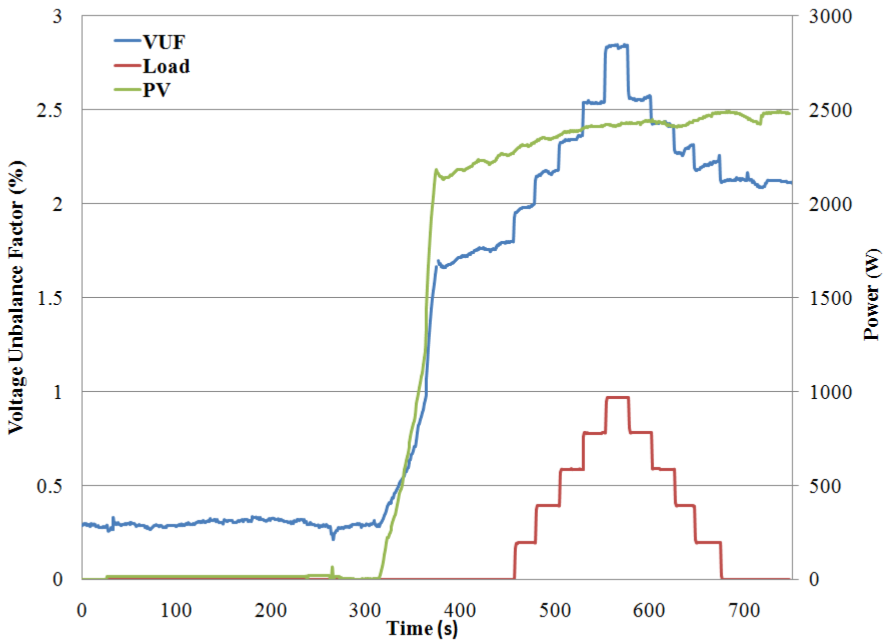

Figure 4.7: Load Demand, PV Power and VUF for PV Inverter and Load Connected at Different Phases

Since the PV inverter and load are connected at different phases, the excess power generated by PV will not be consumed as there is no load connected. In order to mitigate the VUF under this situation, the energy management system will charge the excess power of PV inverter at Phase A to the energy storage and energy storage at Phase C will be used to supply power to the load when the VUF is more than 1%. Figure 4.8 shows the result of VUF after mitigation. When the PV inverter start supply power to the network, the VUF increase up to 1.7%. It takes some time for the energy storage to absorb power from PV inverter at Phase A due to the internal setting of Sunny Island for its protection. In the same time, energy storage at phase C starts to deliver power to load, the VUF is now successfully minimized to below 1%.

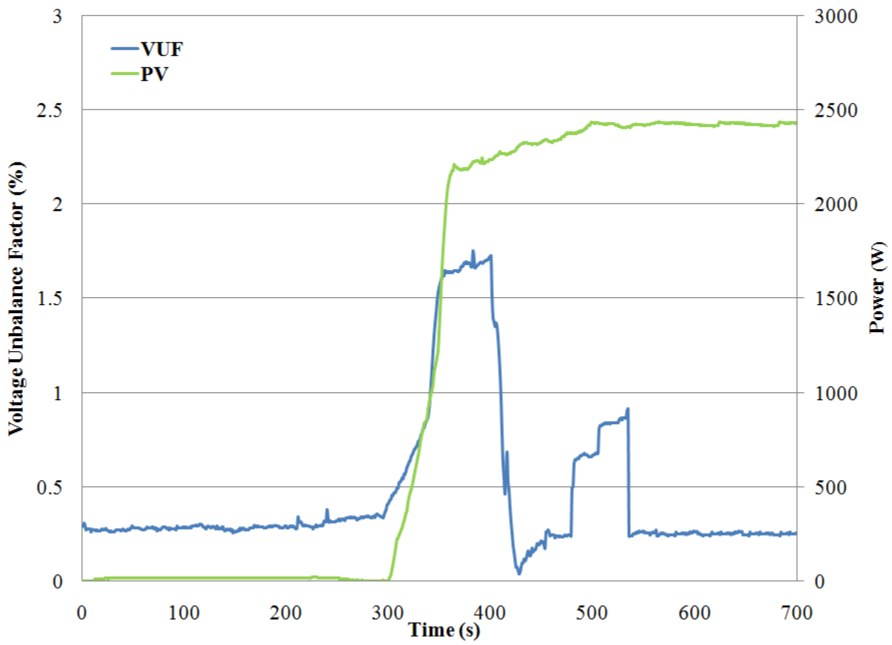

Figure 4.8: VUF for PV Inverter and Load at Different Phases After Mitigation

4.2.4 Uneven Power Demand with PV Inverter and Load Connected at Same Phase

The objective of this experiment is to study the behaviour of voltage in the network when both PV inverter and load are connected at the same phase. Figure 4.9 shows the experiment result of the network. At 280s, PV inverter stars to inject power into the network and the load start to increase its power demand at 420s. The increment in power demand by the load resulted in the reduction of VUF from 1.8% down to 0.75%. This is due to the power generated by the PV is absorbed by the load to prevent excess power flow in the phase and hence the voltage in the phase is kept in balance. In this case study, when the power generated by PV is too high, unbalance will still occur as the load consumption is lower and caused excess power flow in the network.

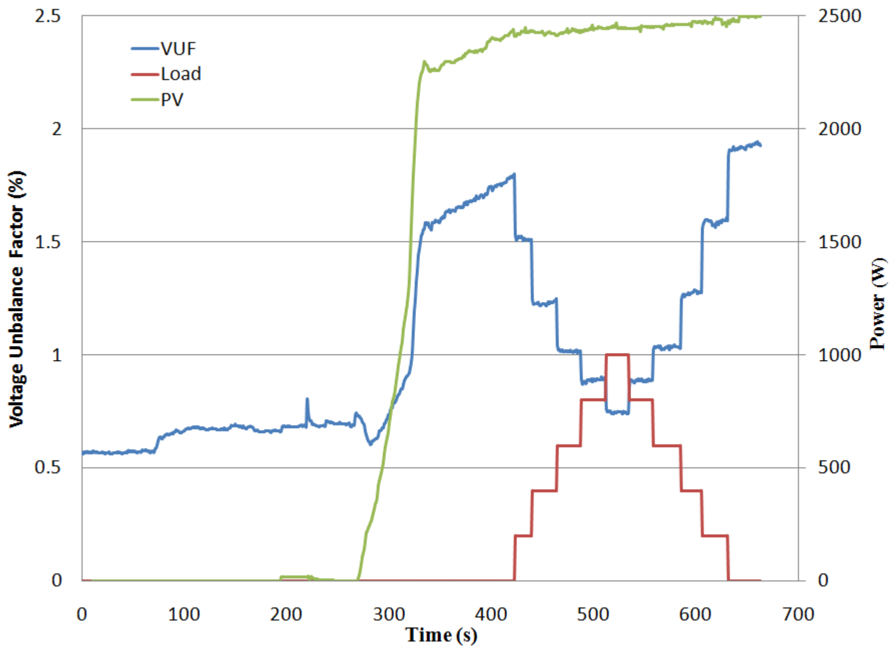

Figure 4.9: VUF for PV Inverter and Load Connected at Same Phase

To overcome the power generated by PV greater than load consumption, the excess power was channeled to the energy storage when the VUF increase to 1% Figure 4.10 shows the experiment result of the VUF in the network. When the PV inverter starts to inject power into the network 70s, the VUF exceed 1% because the load consumption is lower than the generated PV power. In this case, the excess power will be charged and stored into the energy storage resulting in VUF drop from 1.8% to 0.6%. When load is connected, the energy management system will reduce its power absorption from the PV and the load is now supplied by PV power.

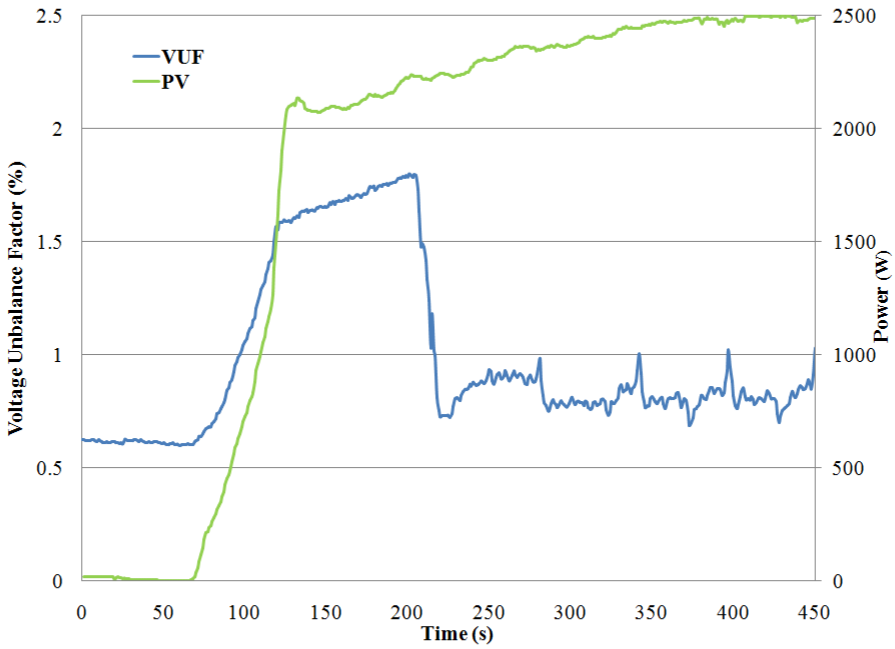

Figure 4.10: VUF for PV Inverter and Load at Same Phase After Mitigation

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The huge impacts on distribution network infrastructure introduced by evolving demand requirements, the low carbon energy drive, increasing energy losses, competitive markets and electrification of new loads became the major concerns for the utilities. Therefore, utilities are required to build more standby power plant to support the grid during daily peak demand period which result in higher cost of electricity and so the electricity tariff. Furthermore, renewable energy sources were introduced as alternative sources. However, due to the intermittent nature, penetration of renewable sources into network caused problem like power quality, instability and reliability of power system.

In this project, an energy management system in conjunction with energy storage system is developed and adopted demand side management techniques to provide energy management for peak clipping and voltage unbalance mitigation due to high penetration of PV systems. From the experiment results, the VUF is reduced effectively with the integration of energy storage system in the network. Through the control algorithm of the energy management system, the energy storage system absorbed the excess power generated by PV systems to maintain the voltage balance in the network. Besides that, the advantages with the integration of energy storage system in the network is that it provide better enhancement of energy generated by PV and PV penetration will help maintain the battery bank at higher state of charge.

The resulting stored capacity can then be used to reduce peak demand of adjacent feeder or as an additional spinning reserve to the network.

On the other hand, demand side management techniques with combination of energy storage system gave great improvement in the load curve, load factor and also reduction in electricity bill due to lowering of maximum demand during peak hours. The energy management system is therefore designed in such a way to deliver power to grid during peak demand period and absorb power from grid during off-peak period. Hence, this system is able to help industrial consumers reduce electricity bill by avoiding maximum demand surcharge during peak demand period from the utility; in the same time helps to reduce the pressure of high demand period as well as cost of operation for utility. Last but not least, the ESS also acts as an uninterruptible power supply (UPS) to the network during power outage. This enhances the reliability of the power system and prevents economic losses during power outage.

As a result, the energy management system together with energy storage system is consider to be a potential solutions to balance supply and demand at system level, provide consumers with control and in a smart distribution network deal with network constraints. Furthermore, this system helps to improve reliability and efficiency of the distribution network and reduction in electricity bill.

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